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ASSESSMENT OF THE GLOBAL POTENTIAL FOR RENEWABLE ENERGY STORAGE SYSTEMS ON SMALL ISLANDS

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Abstract

More than 2,000 small islands (1,000 to 100,000 inhabitants) globally exist. These islands cover a huge potential for the implementation of renewable energies and storage systems. Their power generation is mainly based on expensive diesel power plants. In combination with abundant renewable resources, hybrid renewable energy systems become competitive compared to the existing fossil based power generation. This work reveals the enormous market potential for high share renewable energy solutions including battery storage systems. On a global scale more than 5 GWh of energy storage can be economically installed on these small islands.

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Keywords: hybrid mini-grid, energy system simulation, battery storage

1. Introduction

Worldwide, most small islands rely on expensive and high polluting power generation by diesel generators [1], [2]. This cost intensive energy supply hinders local development and increases the dependency on fossil fuel imports [3]. These problems can be targeted by the implementation of renewable energy (RE) technologies [4], [5], [6]. Renewable resources such as solar irradiation and wind are abundant on most islands [1].

Small islands with up to 100,000 inhabitants can be considered as mini-grids, which are especially interesting for hybridization with photovoltaic (PV) and wind power. Reaching a high share of RE quickly requires battery storage and frequency stabilization systems [7]. To understand the techno-economic optimized configuration of

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PV, wind power, and batteries in a hybrid island system detailed simulations are necessary. These simulations require basic input data such as load profiles and resource data (cf. Fig. 1).

Even though some islands are developed as pilot projects for RE island supply (e.g. El Hierro, Réunion) [8], [9], there is still a lack of knowledge about location, population, load, and energy supply systems on a global scale. Due to this research gap the global potential for RE storage systems on small islands remains unclear. This research work targets to identify and analyze the small islands with the help of geographic information system (GIS) tools and to assess the global RE and storage potential by simulations for each identified island.

2. Methodology

An island is defined as "a naturally formed area of land, surrounded by water, which is above water at high tide" according to United Nations (2012) [10]. Following this definition, all islands larger than 5 m² are extracted from the continental landmasses on a worldwide scale. After identifying the islands' size and location, the local GDP and population is derived from Ghosh et al (2010) [11]. Due to the high resolution of these data (approx. 1 km² pixel size) islands are buffered with a 700 m radius to account for geographical inaccuracies due to the inequalities in resolution regarding the mostly high populated coastal areas of the islands [12].

Afterwards, the techno-economic optimization of the each island's energy system is performed by an inhouse-developed simulation tool*. The model simulates a one-node island energy system with hourly time steps for one reference year taking PV, wind power, diesel gensets and batteries into account (cf. Fig. 1). The output of the optimization is the lowest levelized cost of electricity (LCOE) [13] (cf. Eq. 1 and 2) and the corresponding optimal system configuration.

$$LCOE = \frac{Capex * CRF(WACC, N) + Opex + Costs_{fuel} * Fuel}{El_{consumed}} \qquad (1)$$

Equation 1: Levelized cost of electricity (LCOE) for power systems. Abbreviations stand for: Capital expenditures (Capex); capital recovery factor (CRF); weighted average cost of capital (WACC); project lifetime (N); operation and maintenance expenditures per year (Opex); cost of diesel per liter ($Costs_{fuel}$); consumed diesel per year (Fuel), consumed electricity per year ($El_{consumed}$)

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \qquad (2)$$

Equation 2: Capital recovery factor (CRF). CRF is set according to weighted average cost of capital (WACC) and project lifetime (N).

Local input parameters are diesel costs, solar and wind resources, and load profiles. Each island's energy consumption is derived from the mother country's energy consumption level and energy intensity combined with the local GDP. The shape of the load profile is influenced by climate conditions and a tourism factor [14]. For all islands the same set of techno-economic parameters is chosen. Since the exact diesel power plant composition is not known for each island a generic genset was modeled with some important generalized characteristics. All islands only have a single genset of arbitrary size running at an average efficiency that is independent from the load and only depends on the system size (25 % for < 3MW; 30 % for 3 MW < > 20 MW, and 35% for > 20 MW of peak load). The generic genset can switch from 0 to 100% within one time step, i.e. one hour. The maintenance costs do not depend on operating hours. These simplifications are necessary for this global approach to limit computation time to an acceptable level. It is important to note that the full benefit of batteries (e.g. reducing the genset's maintenance cost and increasing its average efficiency) is not included. As a consequence of the assumptions concerning the genset and the interaction with the batteries we assume to be rather conservative in our simulated results, thus in reality RE

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* MATLAB. ® Version R2011b. The MathWorks, Inc.

technologies and batteries might benefit more than indicated in our findings. All relevant techno-economic parameters are given in the subtext of Figure 1.

The fuel costs are derived from the global diesel price [15] plus transportation costs, which differ due to the remoteness of an island [16]. Another difference is made in the wind turbine selection: For all Caribbean islands and all islands below 10,000 inhabitants a smaller turbine is chosen (easy to erect and hurricane-proof); for all remaining islands larger and less expensive turbines in terms of EUR/kW are selected.

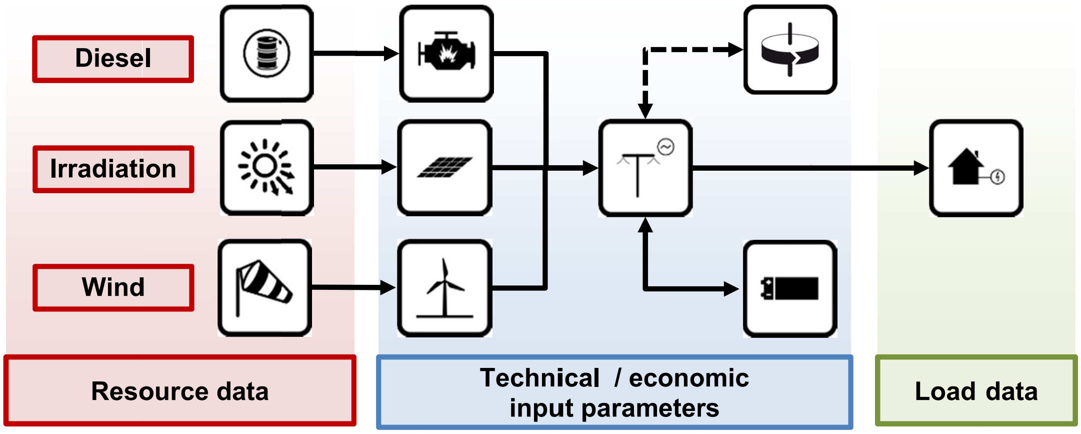

Figure 1: Simulation design and input parameter of hybrid mini-grid.

Resource data: Diesel price (0.63 EUR/l, 3 % annual increase, transportation costs by traveltime [15], [16]), solar irradiation and wind speed by DLR Deutsches Zentrum für Luft- und Raumfahrt. Original data provided by NASA.

Technical: Diesel (efficiency: 25 to 35 %), Battery (round cycle efficiency: 85 %, lifetime: 10 yrs, c-rate: 1:6 kW/kWh), Flywheel (30 % of total renewable capacity, just considered in economics).

Economic: Capital expenditures - Capex (Diesel: 0 EUR/kW, PV: 2,000 EUR/kWp (high costs according to small market size and high transportation efforts), Wind: 1,250 to 1,500 EUR/kW (smaller turbine), Battery: 250 EUR/kWh, Flywheel: 1,000 EUR/kW), Operational expenditures - Opex (Diesel 0 EUR/kW*yr, PV: 2 % of Capex/yr, Wind: 2.5 % of Capex/yr, Battery: 10 EUR/kWh*yr, Flywheel: 0 EUR/kW*yr), Weighted average cost of capital - WACC (7 %), Project lifetime: 20 yrs (conservative approach due to difficult maintenance on islands, wind and PV plants last usually longer than 20 years).

Load: According to GDP, location, and tourism factor (number of overnight stays per year, derived from country level [14]) of island.

3. Results

A previous study, which has been less specific for small islands, but gives an overview on the total global island landscape, reveals that about 740 million people live on islands at the moment [17]. In this study, the GIS analysis detects 2,056 islands between 1,000 and 100,000 inhabitants in total, inhabited by 21 million people overall. More than half of these islands are located in the Pacific Ocean with more than half of the entire population. In total, an electricity consumption of 53 TWh per year is assumed. Again, the Pacific region holds the highest overall electricity consumption, but the Atlantic region is quite close based on the high electricity consumption per capita. The Caribbean region has the highest average electricity consumption and therefore represents the most interesting market region for larger island energy systems. In addition to the electricity consumption the average LCOE of the prevailing diesel systems are calculated resulting in averaged 38 EURct/kWh. These diesel power generation costs are based on an averaged diesel fuel price for next 20 years including three percent price increase per year. Even without diesel price increase the LCOE would be around 29 EURct/kWh. They peak in the Pacific region due to the extreme remoteness of the many small Pacific islands leading to high travel times and transportation costs (cf. Tab. 1).

Table 1: Overview on global small island landscape (1,000 to 100,000 inhabitants).
Regions: Atlantic and Arctic Ocean, Caribbean plus Gulf of Mexico and Bahamas, Indian Ocean, Mediterranean Sea, Pacific Ocean.

Region	Number of Islands	Population (av.)	Population (sum)	GDP (av.) [EUR/cap]
Atl. + Arct. Oc.	416	9,985	4,150,000	18,200
Caribbean +	105	16,160	1,700,000	14,600
Indian Ocean	232	12,210	2,830,000	2,960
Mediterr. Sea	104	10,540	1,100,000	23,500
Pacific Ocean	1,199	9,690	11,620,000	8,660
Total	**2,056**	**10,410**	**21,400,000**	**14,300**

Region	El. cons. (sum) [GWh/year]	El. cons. (av.) [MWh/year]	El. cons. (av. per cap.) [kWh/year* cap]	LCOE Diesel only (av.) [EURct/kWh]
Atl. + Arct. Oc.	18,270	43,920	4,400	36.6
Caribbean +	5,710	54,380	3,370	34.2
Indian Ocean	2,240	9,660	790	38.0
Mediterr. Sea	3,680	35,390	3,345	33.2
Pacific Ocean	22,730	18,970	1,960	39.3
Total	**52,630**	**25,600**	**2,462**	**38.0**

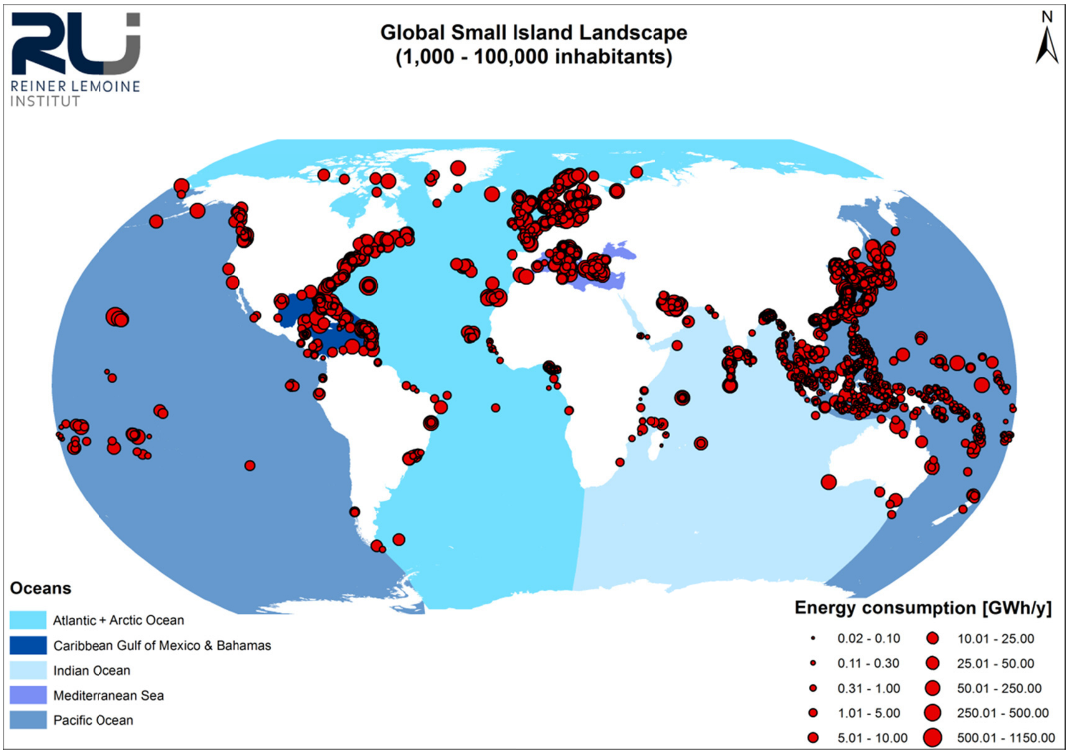

Figure 2: Global map of islands – energy consumption of small islands is highlighted.

To assess the RE storage potential the hybrid system is optimized for each of the 2,056 islands. Two scenarios are performed to understand the additional value of energy storage: Scenario I without and Scenario II with batteries for renewable energy storage. The detailed results of both scenarios are shown in Tab. 2. Even without batteries (Scenario I) all islands possess already a very high RE potential (6 GW_p PV and 12.8 GW wind) and lower LCOE than diesel only (Tab. 2). By introducing REs the LCOE decrease from 38.0 to 30.2 EURct/kWh, equivalent to 20.5 percent cost reduction at a renewable share of 46 %. The potential share of installed capacities of PV and wind power reveals huge differences. While in the Indian Oceanthe PV capacity is marginally higher than the wind power capacity, wind power exceeds PV by more than five times in the Atlantic region. This is a direct consequence of the different local renewable resources. The Pacific region holds by far the highest PV potential and together with the Atlantic region the highest wind power potential in total capacity for small islands.

In Scenario 2 the introduction of batteries leads to an additional decrease of 6 % of the LCOE on average. An overall energy storage capacity potential of 5,300 MWh is calculated increasing the averaged RE share from 46 % to 71 %. Especially in very sunny regions with many small islands such as in the Indian Ocean and Pacific region, the batteries reduce the LCOE and increase the RE share the most. Figure 3 illustrates this phenomenon showing that the prevailing energy storage potential is located in tropical and sub-tropical regions with high solar irradiation and relatively low wind speeds. This has already been assumed in a previous study for IRES 2012 [18] and now proven by this global study. Battery energy storage correlates best with PV by shifting solar power from midday to the demand peaks in the evening hours. This can increase the renewable energy share from around 40 – 50 % to 60 % - 70 % (cf. Pacific and Indian Ocean). The combination of wind power and battery storage is less favorable, reflected in the decrease of economic wind power potential in the techno-economic optimized case by the introduction of batteries. This is due to the higher variability of wind power generation with sometimes weeks without produced wind energy. Battery capacities have to be quite high to overcome these periods of low wind speeds, which is usually uneconomical. In these cases, if seasonal storage is necessary, power-to-gas systems can be an economically extension to battery storage to store wind power over long-time periods [19]. However power-to-gas systems are not considered in the simulation model of this study as small islands mainly lacking substantial infrastructure for these systems such as gas storage facilities and power plants.

Table 2: Results for techno-economic optimization of hybrid island energy supply systems (1,000 to 100,000 inhabitants) – Scenario I is without battery storage, Scenario II is with battery storage, results for Scenario II are in relation to Scenario I in percent.
Regions: Atlantic and Arctic Ocean, Caribbean plus Gulf of Mexico and Bahamas, Indian Ocean, Mediterranean Sea, Pacific Ocean.

Region	Scenario	PV (sum) [MWp]	Wind (sum) [MW]	Storage (sum) [MWh]	LCOE (av.) [EURct/kWh]	RE share (av.)
Atl. + Arct. Oc.	Scen I	930	5,320	n/a	26.3	48%
	Scen II	+21%	-1%	930	-1.9%	58%
Caribbean +	Scen I	910	1,210	n/a	24.3	57%
	Scen II	+9%	-2%	360	-1.6%	65%
Indian Ocean	Scen I	420	370	n/a	29.7	44%
	Scen II	+76%	-30%	1,240	-6.7%	65%
Mediterr. Sea	Scen I	550	770	n/a	25.8	47%
	Scen II	+10%	-1%	230	-1.2%	55%
Pacific Ocean	Scen I	3,390	5,090	n/a	30.2	44%
	Scen II	+19%	-5%	2,550	-7.0%	71%
Total	**Scen I**	**6,200**	**12,760**	**n/a**	**30.2**	**46%**
	Scen II	**+21%**	**-4%**	**5,310**	**-5.6%**	**71%**

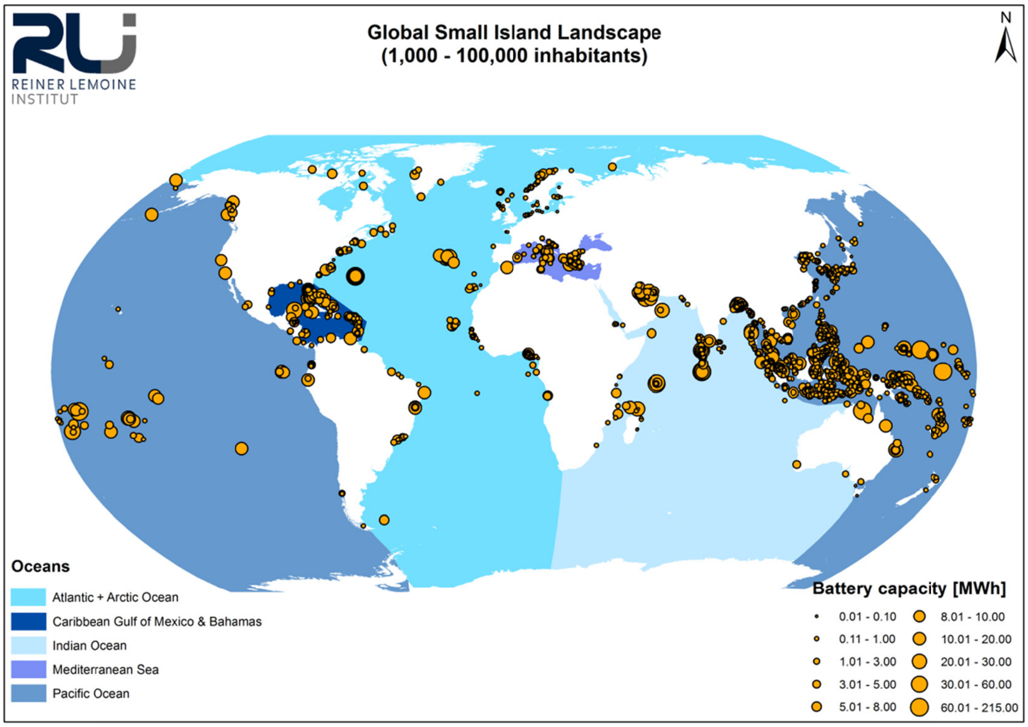

Figure 3: Global map of islands – Installed battery power of small islands is highlighted for optimized hybrid systems.

4. Conclusion

According to the optimization all selected small islands profit from the introduction of REs in the long run. This introduction would bring economic benefits even under a conservative fossil fuel price increase of 3 % per year compared to an average historic increase of 5 % per year during the last 20 years [15]. Additional implementation of batteries leads to further cost reductions particularly in tropical and sub-tropical (Fig. 3) regions with high solar irradiation and low wind speeds. The overall rise of the renewable share by 25 % by introducing batteries into the systems shows the enormous vale of battery storage systems for the renewable energy implementation. The higher the renewable share the lower is the diesel consumption on these islands. With less diesel consumption the power generation systems are less dependent on price-volatile diesel fuels, which reduce the financial risks for the islands' energy supply.

In addition the tropical and sub-tropical regions show low seasonality within their solar irradiation which enables high share renewable energy systems with short term energy storage technologies such as the assumed batteries. In regions with high share of wind power coming with higher variability and seasonality, batteries cannot significantly improve the economic viability of the energy supply system. In this case, long term storage technologies such as pumped hydropower storage or hydrogen and power to gas systems are required [19].

The global potential for energy storage by batteries in renewable energy island systems for small islands between 1,000 and 100,000 inhabitants is calculated to be 5.3 GWh. The Pacific region has the highest regional potential of 2.55 GWh. These potentials are derived for battery costs of 250 EUR/kWh [20], [21] and a fixed c-rate (ratio of energy and capacity) of 1:6 kW/kWh. Since different technologies with different c-rates exist, a further step to improve the model is to leave the c-rate open in the optimization process. This will allow the model to decide whether a battery system acts predominantly as power or energy storage and will allow a more differentiated view on the potential.

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